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TITLE: INTEGRATED HEAT PIPE-THERMAL STORAGE SYSTEM PERFORMANCE EVALUATION

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INTEGRATED HEAT PIPE-THERMAL STORAGE SYSTEM PERFORMANCE EVALUATION

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ABSTRACT

Performance verification tests of an integrated heat pipe-thermal energy storage system have been conducted. This system is being developed as a part of an Organic Rankine Cycle-Solar Dynamic Power System (ORC-SDPS) receiver for future space stations. The integrated system consists of potassium heat pipe elements that incorporate thermal energy storage (TES) canisters within the vapor space along with an organic fluid (toluene) heater tube used as the condenser region of the heat pipe. During the insolation period of the earth orbit, solar energy is delivered to the surface of the heat pipe elements of the ORC-SDPS receiver and is interna y transferred by the potassium vapor for use and storage. Part of the thermal energy is delivered to the heater tube and the balance is stored in the TES units. During the eclipse period of the orbit, the stored energy in the TES units is transferred by the potassium vapor to the toluene heater tube. A developmental heat pipe element was fabricated that employs axial arteries and a distribution wick connecting the wicked TES units and the heater to the solar insolation surface of the heat pipe. Tests were conducted to verify the heat pipe operation and to evaluate the heat pipe/TES units/heater tube operation by interfacing the heater unit to a heat exchanger. The heat pipe assembly was operated through the range of design conditions from the nominal design input of 4.8 kW and up to a maximum of 5.7 kW. Axial heat flux was varied up to 15 w/cm^2 to simulate misalignment of solar optics. Thermal cycle tests were conducted to verify the thermal storage and discharge of the TES units during insolation and eclipse modes. Details of the test procedures and results of the tests are presented.

INTRODUCTION

The organic Rankine cycle (ORC) solar dynamic power system (SDPS) is one of the prime candidates for Space Station prime-power application. The low earth orbit of the Space Station will result in approximately 34 minutes of the 94-minute orbital period in eclipse without solar energy being received. For this application, the SDPS will use thermal energy storage (TES) material to provide a constant power output. Sundstrand Corporation is developing a ORC-SDPS candidate for the Space Station that uses toluene as the working fluid and LiOH for the TES material.[1] Potassium heat pipes, key elements in the development of this system, are used to absorb and transfer the solar energy within the receiver cavity (see Fig. 1). The heat pipes incorporate the TES containers and the toluene

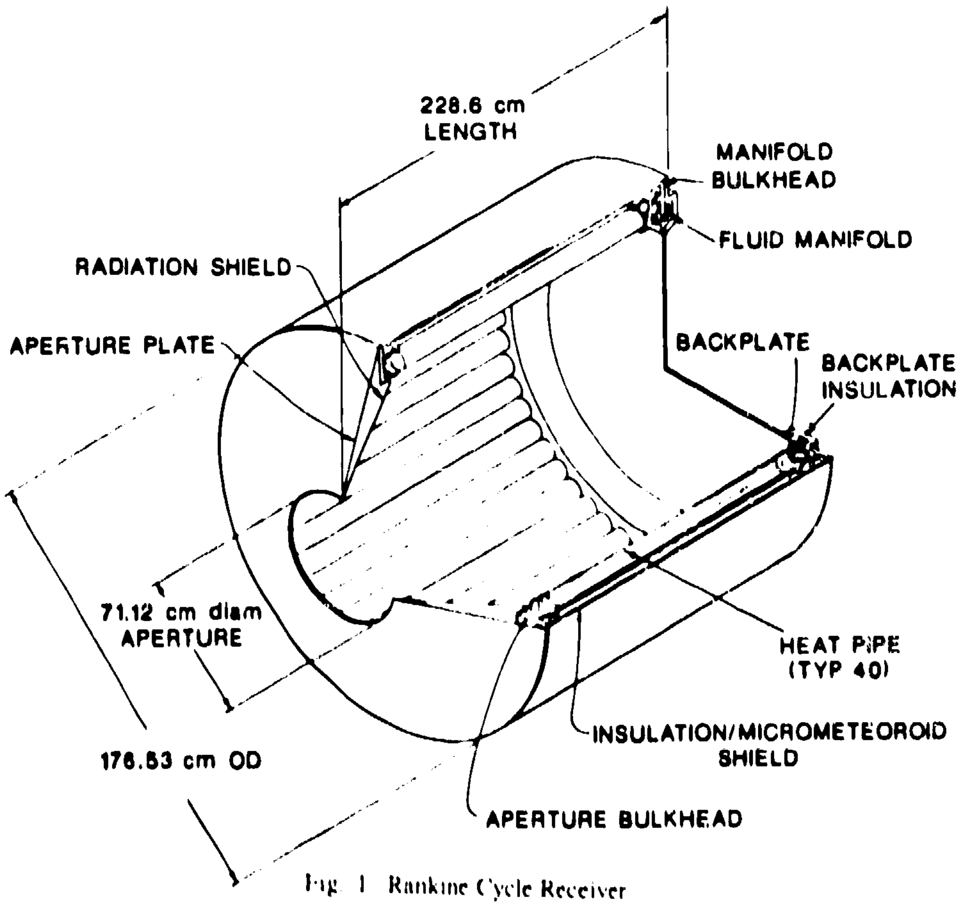

Fig. 1 Rankine Cycle Receiver

heater surface within the vapor space of the heat pipe. Each heat pipe provides a passive means of obtaining high thermal conductance between the heat pipe surface, the heater tube, and the TES containers. The heat pipe transforms the nonuniform heat flux within the solar receiver cavity to a constant flux at potassium vapor interface in the heat pipe. The high-axial-heat transport provides a nearly constant temperature interface with the TES modules and the heater tube. Thus, the high-intensity, non-uniform solar energy incident in the receiver is made available to the large surface area of the TES canisters and to the high-power density surface of the toluene heater at uniform conditions. The potassium vapor transport provides a means of switching the thermal energy flow from the solar input to the TES material or to the heater surface with minimal temperature difference.

The requirements imposed on the solar receiver heat pipes are similar to conventional heat pipes, but with some differences in operational characteristics. The solar radial flux varies from end to end with a peak flux of about 7.5 w/cm^2 (with design margin of 2 or 15 w/cm^2) approximately 50 cm from one end. The operating temperature is limited to 775 K maximum in the vapor space of the heat pipe by cycle operating conditions. Average input to each heat pipe is 4.8 kW with a maximum of 5.7 kW possible due to misalignment of solar optics. During eclipse, the heat pipe is required to continue to function in a transfer mode using the latent heat of the LiOH as the heat source to provide heat throughput to the toluene heater. The operating requirements and internal flow paths for the heat pipe vary according to the mode of system operation (insolation or eclipse).

A developmental heat pipe was constructed with a wick structure designed to provide liquid return for the varied heat transfer performance during operation in a gravity-free environment. The wick was optimized for the heat pipe internal configuration under maximum performance conditions with a secondary goal of minimum material use to ensure light weight.(2) The resulting heat pipe design, shown in Fig. 2, was tailored to the energy input requirements; Energy transport to the calorimeter tube (simulated ORC heater tube) and TES canisters, And energy transport from the TES canisters to the calorimeter tube during discharge. The work reported in this paper was directed to the experimental performance evaluation of the integrated heat pipe-thermal storage element operating in a temperature range of 725 to 775 K and a 4.8 to 5.7 kW power-input range.

FABRICATION AND PROCESSING

The heat pipe was constructed from stainless steel tubing 190.5 cm in length, with an outside diameter of 12.7 cm and wall thickness of 0.127 cm. Three layers of 100 mesh stainless screen were placed against the inner wall for circumferential fluid distribution. Three layers of 100 mesh were also placed over the TES units and over the heater tube to collect the condensate during operation. The three layers around the heater tube were arranged to form a pedestal, which provided for a fluid path between the heater tube and the circumferential fluid distribution wick. Axial fluid distribution was provided for by 6 arteries, 2 between each of the TES units and the inner wall and two between the heater tube and the screen pedestal. The TES units and heater tube were positioned internal to the heat pipe and held in place by end cap supports and internal stainless steel skeletal supports.

All internal heat pipe parts were cleaned and vacuum-fired prior to TIG weld assembly. Before potassium charging, the heat pipe assembly was vacuum fired at 825 K. Potassium was introduced into the heat pipe by vacuum distillation. Upon completion of the potassium distillation, the heat pipe was positioned horizontally and heated uniformly over its entire length to distribute the potassium charge and to ensure complete wetting of the interior surface and filling of the arteries.

TEST OBJECTIVES

The objectives of the heat pipe testing were to characterize the heat pipe for the operating conditions of NASA's Space Station and included the following tests:

(1) Heat pipe operational verification test without calorimetry.

(2) Steady state performance tests, including maximum calorimeter power.

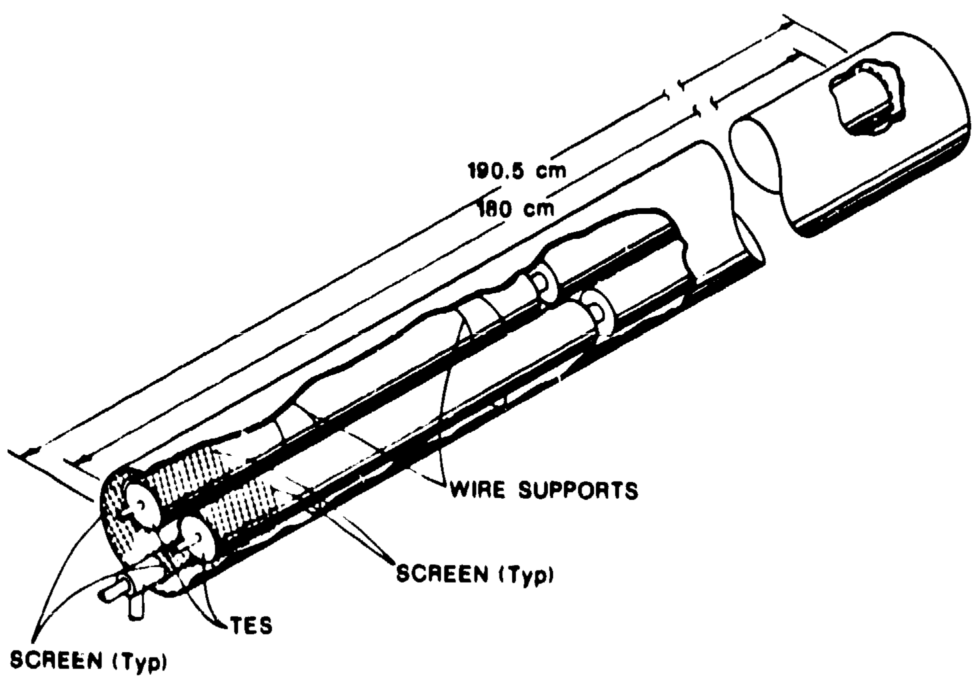

Fig. 2 Axial heat pipe with thermal storage unites

(3) Verification of proper thermal storage charge and discharge.

(4) Adverse gravity tests.

(5) Maximum heat flux test.

TEST ARRANGEMENT AND APPARATUS

A vacuum test chamber was used to conduct the wet-in and performance testing of the heat pipe element. The test chamber shown in Fig. 3 contained ports for power leads, vacuum pumping, and for instrumentation, windows for visual observation of the heat pipe during operation, and a feed through for the calorimeter attachment to the heater tube. The simulated solar heat input was provided by a variable zone r.f. coil. This coil was separated into four zones, (fig 4), each providing a different radial heat input flux into the heat pipe.

The radial heat input flux could also be varied by moving a coil closer to or further away from the heat pipe wall. This method provides an average radial heat input over four distinct zones. Each coil is shaped to deliver heat to a semicylindrical portion over the length of the heat pipe. The coil patterns were designed to approximate the insolation pattern on the inner surface of the receiver cavity.

Heat loss on the back half of the surface of the heat pipe was kept at a minimum by radiation shielding. Sixteen thermocouples were attached to the external surface of the heat pipe to monitor the temperature profile circumferentially and axially. The locations are shown in Fig. 5.

EXPERIMENTAL PROCEDURES

An initial test was conducted to verify the heat pipe start up operation from the frozen state and to demonstrate freedom from non-condensable gas contamination. Initial start up from the frozen condition of the working fluid was accomplished by increasing the power input to the test element to obtain ≤ 5 K/min temperature rise rate while maintaining vacuum chamber vacuum within the 10^{-5} Torr range. The heat pipe element was stabilized at 775 K and monitored for gas contamination build-up. The end thermocouples showed no decrease in temperature after one hour of steady state operation, indicating little or no gas accumulation. The no-calorimetry test was followed with a steady state test with calorimetry.

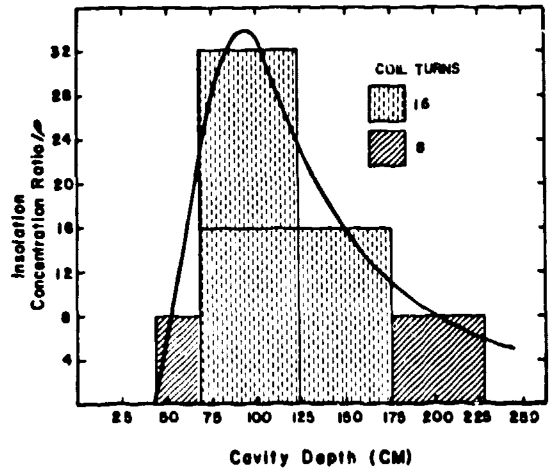

Fig. 4 Insolation concentration versus cavity depth

Steady State Tests. The calorimeter tube of the heat pipe assembly was connected to the Syltherm 800 flow system (furnished by Sundstrand) that simulated the toluene flow system as shown in Fig. 6. Tests were conducted to satisfy the conditions of 4.8 kW heat throughput for normal operation and 5.7 kW heat throughput for an upper limit capability. Steady state operations were attained at 5 kW and 6.1 kW to satisfy the test requirements. However, these powers were obtained at relatively low temperatures (665-675 K). This condition was caused by turbulent fluid flow through the calorimeter tube, resulting in a substantially higher heat transfer coefficient of the fluid than was used in the design. Various arrangements were made to alter the flow system to maintain laminar flow with no success. A power of 7.57 kW at 730 K was reached during these trials, indicating the heat pipe test element had the capability to operate at a power throughput 50% greater than normal.

To satisfy the remaining test conditions, an alternate method of system heat removal was incorporated into the system. Instead of direct coupling of Syltherm 800 fluid to the heater tube wall, a gas gap was used between the heater tube and a separate tube that contained the heat transfer fluid. By varying a gas mixture of argon and helium within this gap, from 1 to 8 kW heat throughput could be transferred to the Syltherm. In subsequent tests, this arrangement was used with appropriate gas mixture control to establish the

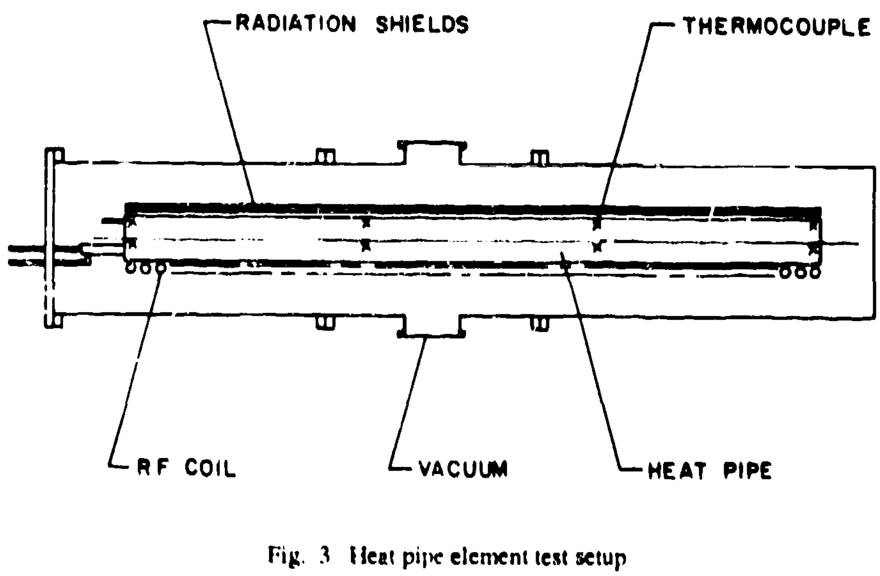

Fig. 3 Heat pipe element test setup

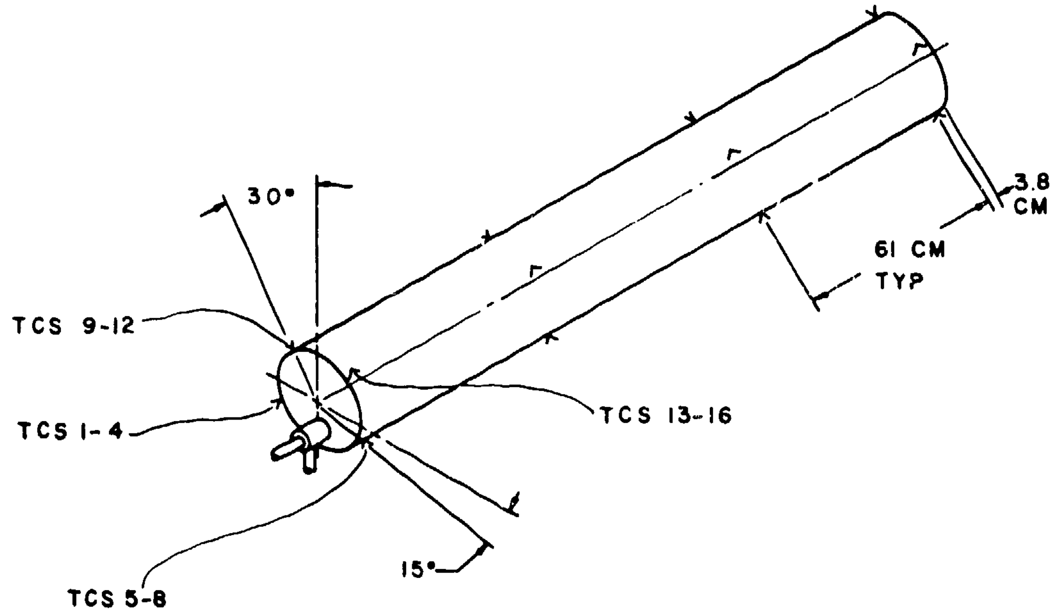

Fig. 5 Thermocouple location

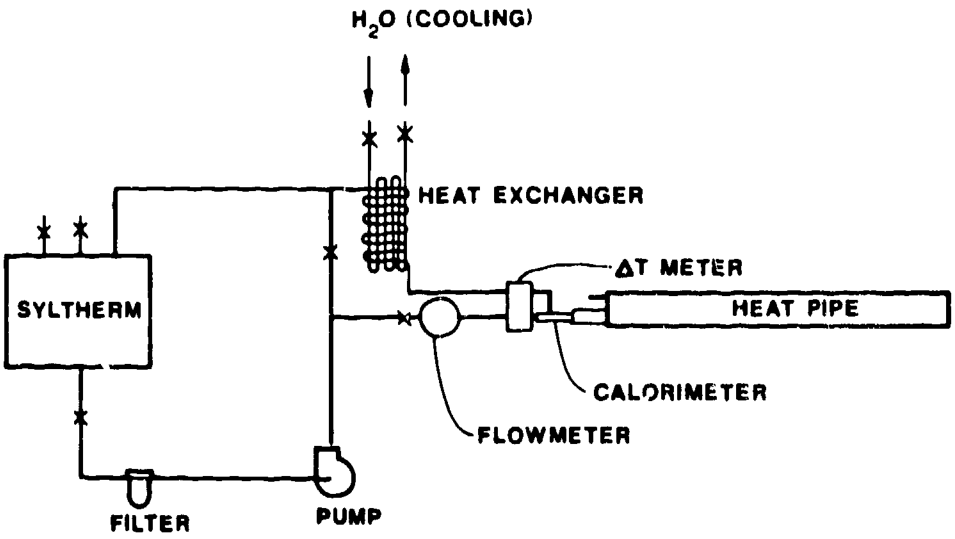

Fig. 6 Calorimeter setup

design value heat throughput at design temperature.

Thermal Charge and Discharge Tests. Thermal charge and discharge of the internal thermal storage canisters was conducted to simulate an earth orbit cycle. The test setup used for steady state testing was used for this test. The test cycle was reduced to 75 % of earth orbit (45 min insolation and 26 min eclipse) to accommodate the actual mass of salt. One of four TES canisters failed final weld inspection and was replaced with a dummy canister. Two test cycles were conducted with the heat pipe evaporator and heater tube in the 6 o'clock position.

After the initial startup, a condition was obtained in which the thermal energy canisters and the heat pipe were at a temperature of 735 K with a power throughput of 5.2 kW. The power input was held constant and the gas mixture within the gas gap was adjusted to allow only 3.0 kW throughput with the remaining 2.0 kW being stored in the storage canisters. The temperature of the heat pipe increased during this phase. When the temperature of the heat pipe reached 775 K, the first eclipse cycle was started and held for 26 min followed by an insolation period of 45 min as shown in Fig. 7. A second eclipse cycle was conducted prior to termination of test. The average power throughput was 3.0 kW during the test cycles. The peak temperature swing was from 730 K to 780 K or 755 ± 25 K.

The test cycle shown in Fig. 8 was conducted in the same way as the first, except that instead of the starting condition being 5.0 kW at 735 K (10 K lower than the 745 K m.p. of LiOH storage material) the starting point was 5.0 kW throughput at 720 K. The average throughput during cycling was 3.0 kW and the temperature swing was 714 K to 762 K or 738 ± 24 K.

During one other test cycle, the calorimeter tube and the r.f. heat input were changed from the 6 o'clock position to the 12 o'clock position to test the heat pipe operation with

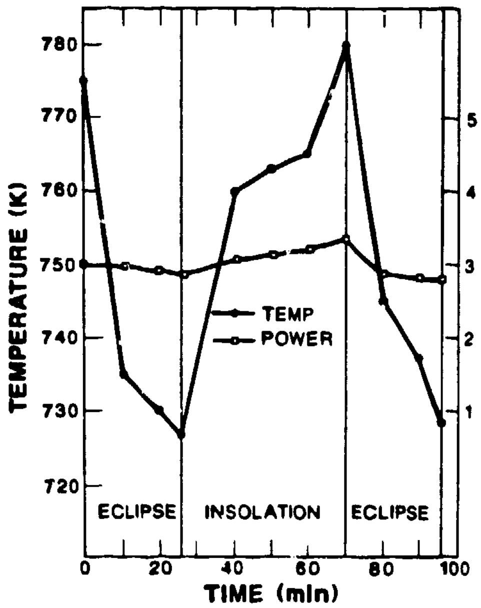

Fig. 7 TES canister fully charged at start of eclipse

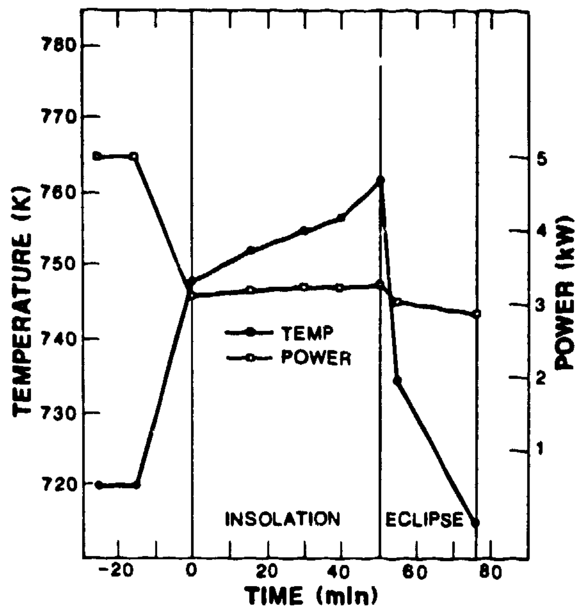

Fig. 8 TES canisters fully discharged at start of insolation

the evaporator in an adverse "g" attitude. The heat pipe element was operated satisfactorily at a 5 kW-heat throughput at 450 K; however, when the gas mixture was adjusted to remove 3 kW through the calorimeter and allowed the heat pipe temperature to rise to 476 K, a dry out occurred in the evaporator, thus terminating the test. The initial design analysis for the heat pipe element indicated that the available capillary head was 1962 Pa, using a pore radius of $.83 * 10^{-4}$ M, and that the heat pipe evaporator would operate in an adverse "g" attitude, with some margin in the total pressure drop.[2] A review analysis indicates that the actual pore radius is $1.3 * 10^{-4}$ M and that the available capillary head is 1221 Pa. This review indicated that the sum of the pressure drops in the wick structure during full-power operation with adverse "g" exceeded the available head and, therefore, limited performance.

Peak-Heat-Flux-Capability Test. A test was conducted where the input heat flux was varied axially to demonstrate the design-peak-heat-flux capability of 15 watts/cm^2. An r.f. coil was fabricated to provide greater than 5 kW heat input over an area limited to a zone that received 15 watts/cm^2 or more. The total length of the heat input region was reduced from 190.5 cm to 35.6 cm and covered an area of 514 cm^2. More than 15 watts/cm^2 were put into the heat pipe element over an area of 38.8 cm^2, based on measured throughput and radiation-loss calculations. The heat pipe was isothermal within 5 K at a temperature of 733 K for 15 minutes with a calorimeter power of 3 kW. No hot spots or abnormal behavior occurred.

CONCLUSION

A potassium heat pipe, incorporating thermal energy storage elements has been fabricated and tested to the functional requirements of use in the solar receiver of an organic Rankine cycle-solar dynamic power system. Simulated absorption of solar energy was successfully demonstrated with this heat pipe by using variable r.f. heat input coil. The heat pipe assembly was operated at design input powers of 4.8 and 5.7 kW and at a maximum throughput of 7.57 kW. Thermal cycle tests to simulate the insolation and eclipse periods demonstrated the successful charge and discharge of the TES canisters. Axial flux variations to 15 w/cm^2 were also successfully demonstrated. Therefore, all test objectives were successfully accomplished.

The performance verification tests show that an integrated heat pipe-thermal energy storage system meets the functional requirements of (1) absorbing the solar energy reflected by the concentrator, (2) transporting the energy to the organic Rankine heater, (3) providing thermal storage for the eclipse phase and (4) allowing uniform discharge from the thermal storage to the heater.

ACKNOWLEDGMENT

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